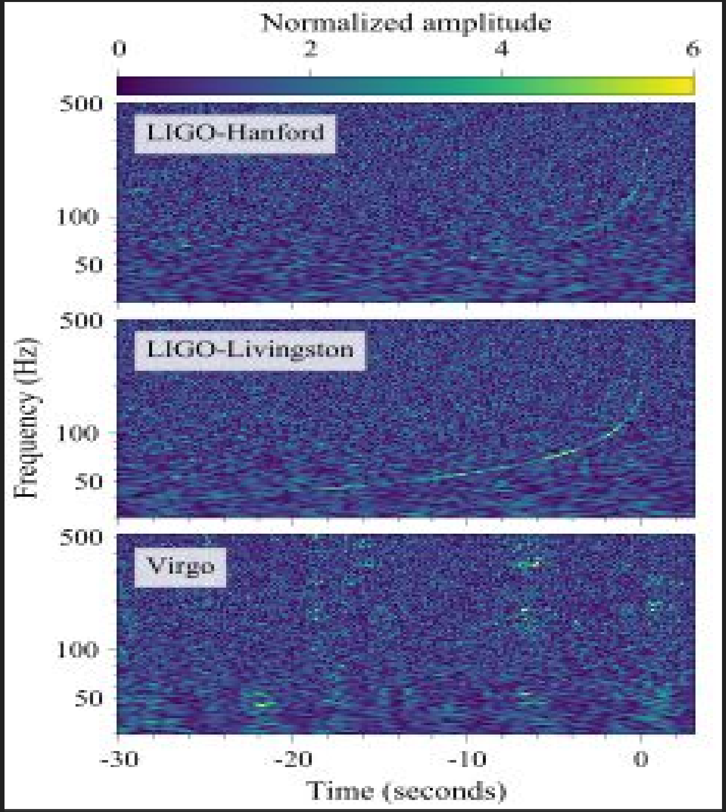
Gravitational-wave Astronomy

Alexander Nitz
Max Planck Institute for Gravitational Physics - Albert Einstein Institute
On behalf of the
LIGO Scientific Collaboration

MAX-PLANCK-GESELLSCHAFT

GW170817

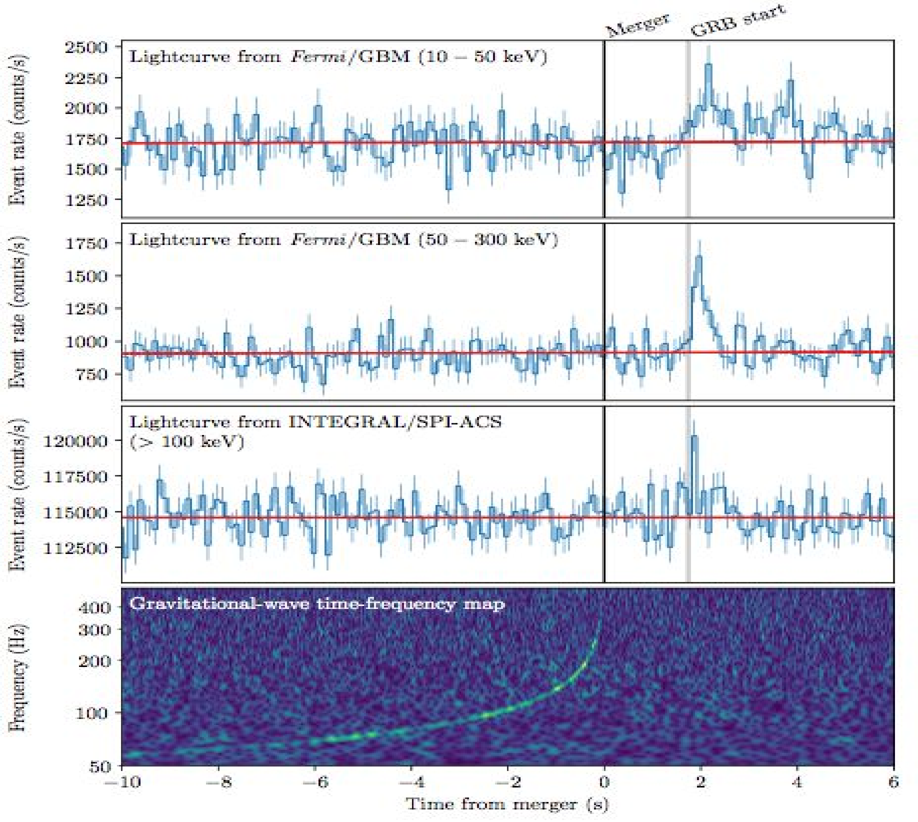


Both LIGO and the Virgo detectors were operational at the time of the signal - **12:41:04.4 UTC**

GW170817 swept through the detectors' sensitive band in ~100s ($f_{start} = 24Hz$)

Loudest (network SNR of 32.4), closest and best localized signal signal ever observed by LIGO/Virgo

GRB170817A



GRB170817A occurs (1.74 ± 0.05) seconds after GW170817

It was autonomously detected in-orbit by Fermi-GBM (GCN was issued 14s after GRB) and in the routine untargeted search for short transients by INTEGRAL SPI-ACS

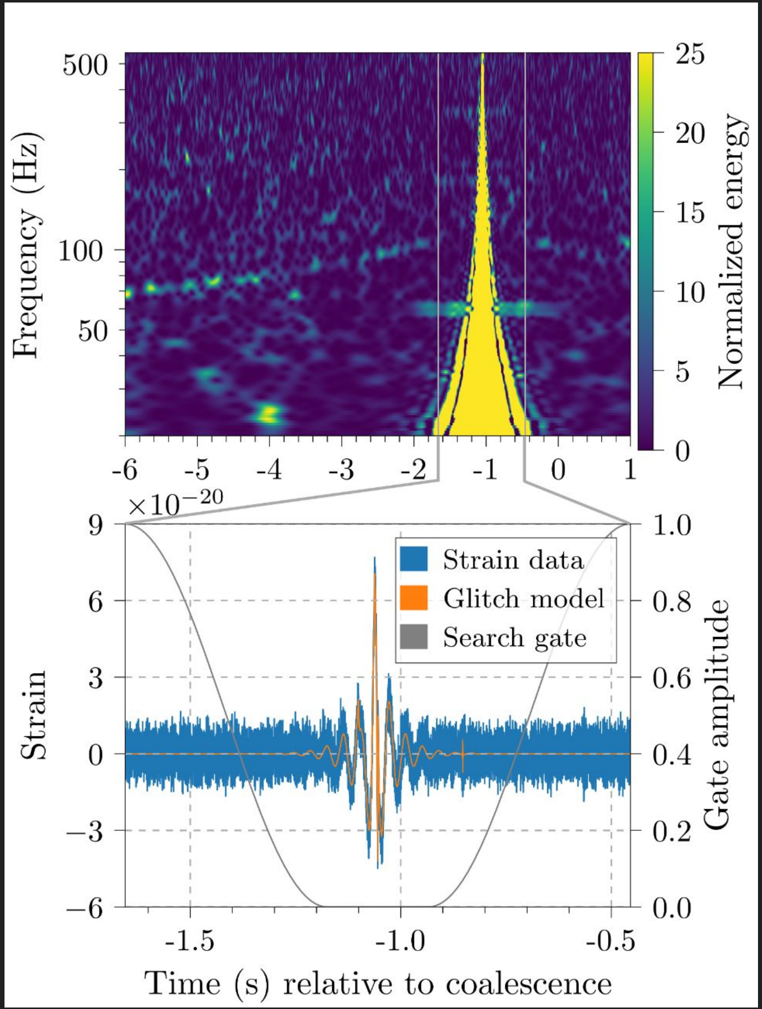
Probability that GW170817 and GRB170817A occurred this close in time and with location agreement by chance is 5.0×10^{-8} (Gaussian equivalent significance of 5.3σ)

B. P. Abbott et al., *Gravitational Waves and Gamma Rays from a Binary Neutron Star Merger: GW170817 and GRB170817A*, ApJL, XX LXX (2017)

GW170817 Story

- GW170817 was initially identified in LIGO-Hanford by a low latency binary-coalescence search
- A short instrumental noise transient (“glitch") appeared in LIGO-Livingston 1.1 seconds before the coalescence time
- Similar noise transients are registered roughly once every few hours in each of the LIGO detectors
    - no temporal correlation between the LIGO sites

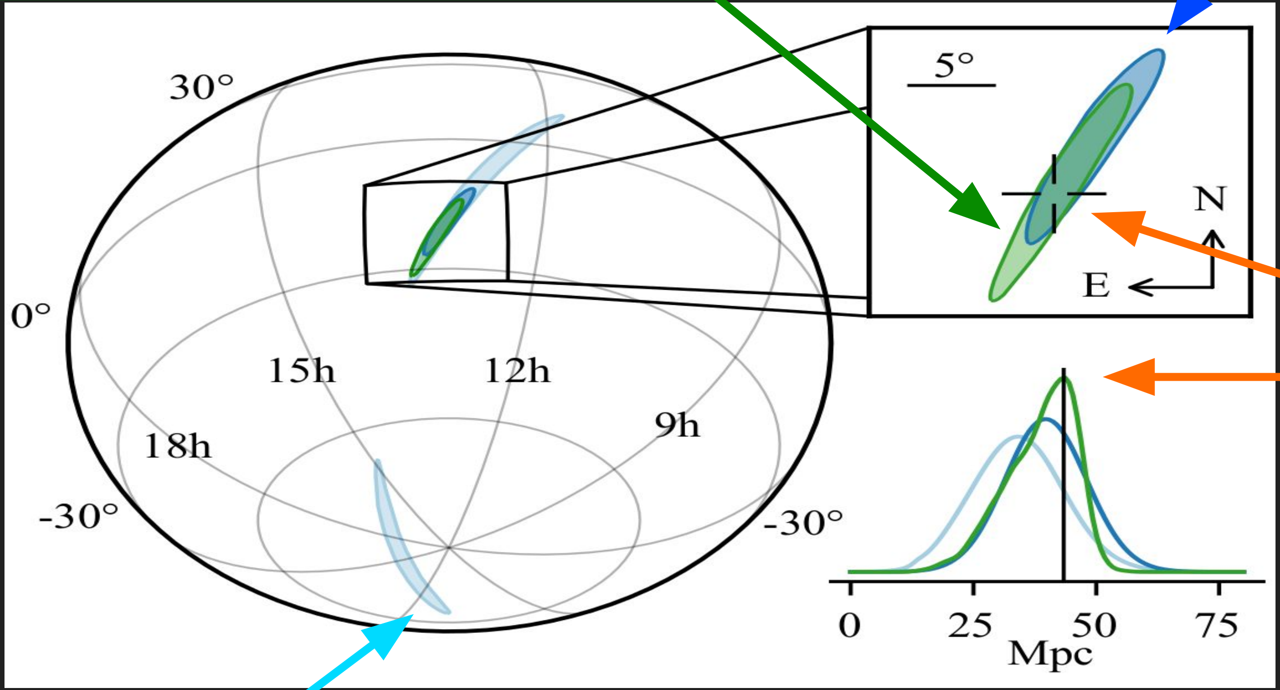
- A rapid binary-coalescence re-analysis the LIGO and Virgo data (with the glitch suppressed) confirmed the presence of a significant coincidence! This led to the first HLV skymap



All numbers are quoted at 90% confidence

Higher latency localisation - LIGO-Virgo:
28 deg^2

Rapid localisation - LIGO-Virgo:
31 deg^2



Position and distance to NGC 4993

Rapid localisation - LIGO:
190 deg^2

Luminosity distance: 40^{+8}_{-14} Mpc

B. P. Abbott et al., *GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral*, Phys. Rev. Lett., 119, 161101 (2017)

Multimessenger Observations

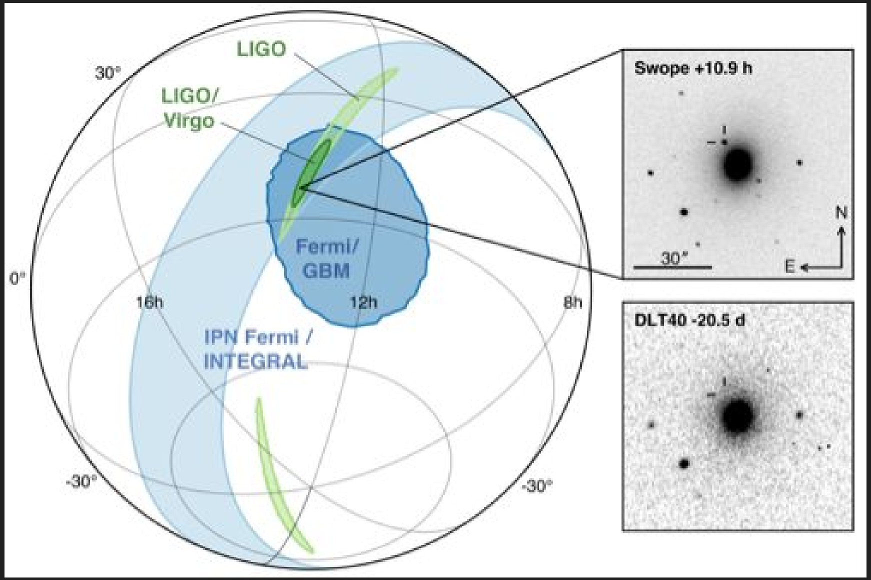
GW170817 - August 17, 2017 12:41:04 UTC

GW170817A - August 17, 2017 12:41:06 UTC

LIGO-Virgo GCN reporting BNS signal associated with the time of the GRB - August 17, 2017 13:21:42 UTC

LIGO-Virgo GCN reporting the first HLV skymap- August 17, 2017 17:54:51 UTC

Bright optical transient (SSS17a, now IAU identification AT2017gfo) discovered in NGC 4993 by One Meter, Two Hemisphere Team - August 18, 2017 01:05 UTC

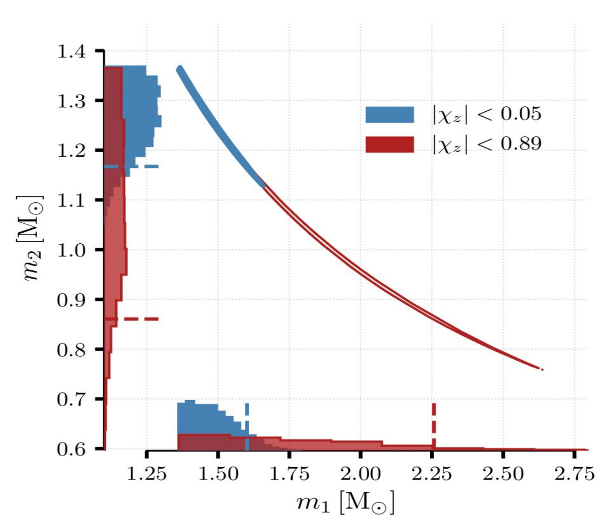


Five other teams took images of the transient within an hour of the 1M2H image (and before the SSS17a announcement)

Approximately 70 ground- and space- based observatories followed-up on this event

B. P. Abbott et al., *Multi-messenger Observations of a Binary Neutron Star Merger,* ApJL, XX, LXX (2017)

BNS properties



The properties of gravitational-wave sources are inferred by matching the data with predicted waveforms

For low orbital and gravitational-wave frequencies the evolution of the frequency is dominated by chirp mass

As orbit shrinks the gravitational-wave phase is increasing influenced by relativistic effects related to the mass ratio

Component masses are affected by the degeneracy between mass ratio and the aligned spin components χ_{1z} and χ_{2z}

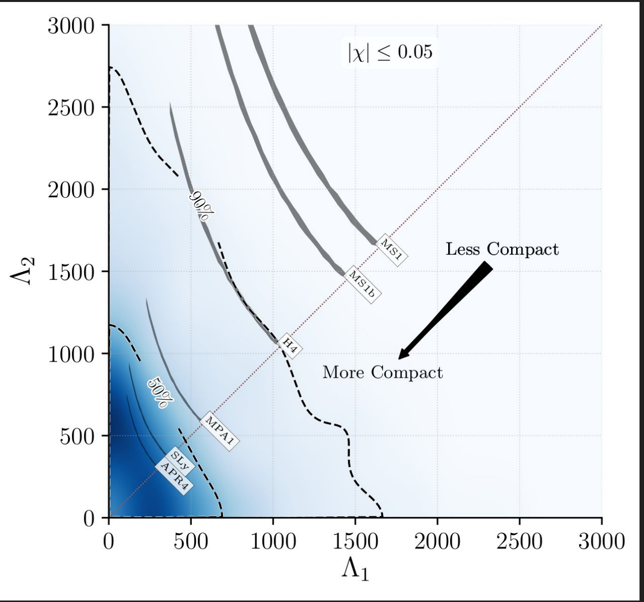
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

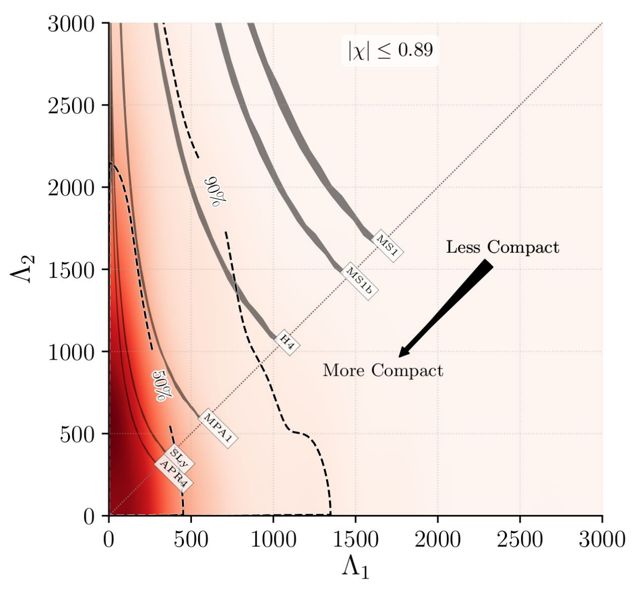
- $|\chi| \leq 0.89$ limit imposed by available rapid waveform models
- $|\chi| \leq 0.05$ limit consistent with the observed population of BNS which will merge in Hubble time

	Low-spin priors ($|\chi| \leq 0.05$)	High-spin priors ($|\chi| \leq 0.89$)
Primary mass m_1	$1.36 - 1.60\ M_\odot$	$1.36 - 2.26\ M_\odot$
Secondary mass m_2	$1.17 - 1.36\ M_\odot$	$0.86 - 1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002}\ M_\odot$	$1.188^{+0.004}_{-0.002}\ M_\odot$
Mass ratio m_2/m_1	0.7 – 1.0	0.4 – 1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01}\ M_\odot$	$2.82^{+0.47}_{-0.09}\ M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025\ M_\odot c^2$	$> 0.025\ M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
using counterpart location	$\leq 31°$	$\leq 31°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

B. P. Abbott et al., *GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral*, Phys. Rev. Lett., 119, 161101 (2017)

BNS properties





$\Lambda \sim k_2(R/m)^5$

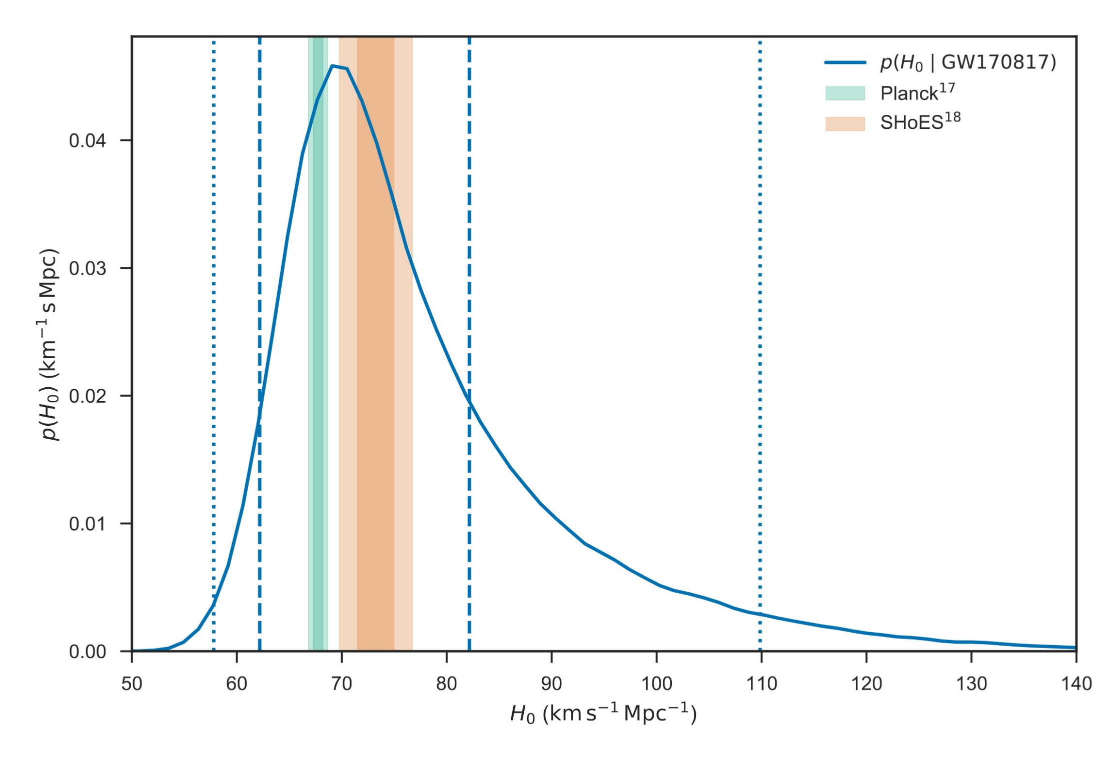
k_2 - second Love number

R - stellar radius

m - mass of neutron star

- The Λ_1 and Λ_2 parameters characterize the size of the tidally-induced mass deformations of each neutron star
- Probability density for the tidal deformability parameters using the post-Newtonian model.
- Shaded gray - predictions for tidal deformability given by a set of representative equations of state (all of which support stars of 2.01 $M_\odot$)
- Equations of state that produce less compact stars, such as MS1 and MS1b, predict Λ values outside the 90% contour

GWs as standard sirens



$$v_H = H_0 d$$

d - distance to the source
Use the GW distance estimate

v_H - local “Hubble flow” velocity of the source
Use optical identification of the host galaxy NGC 4993

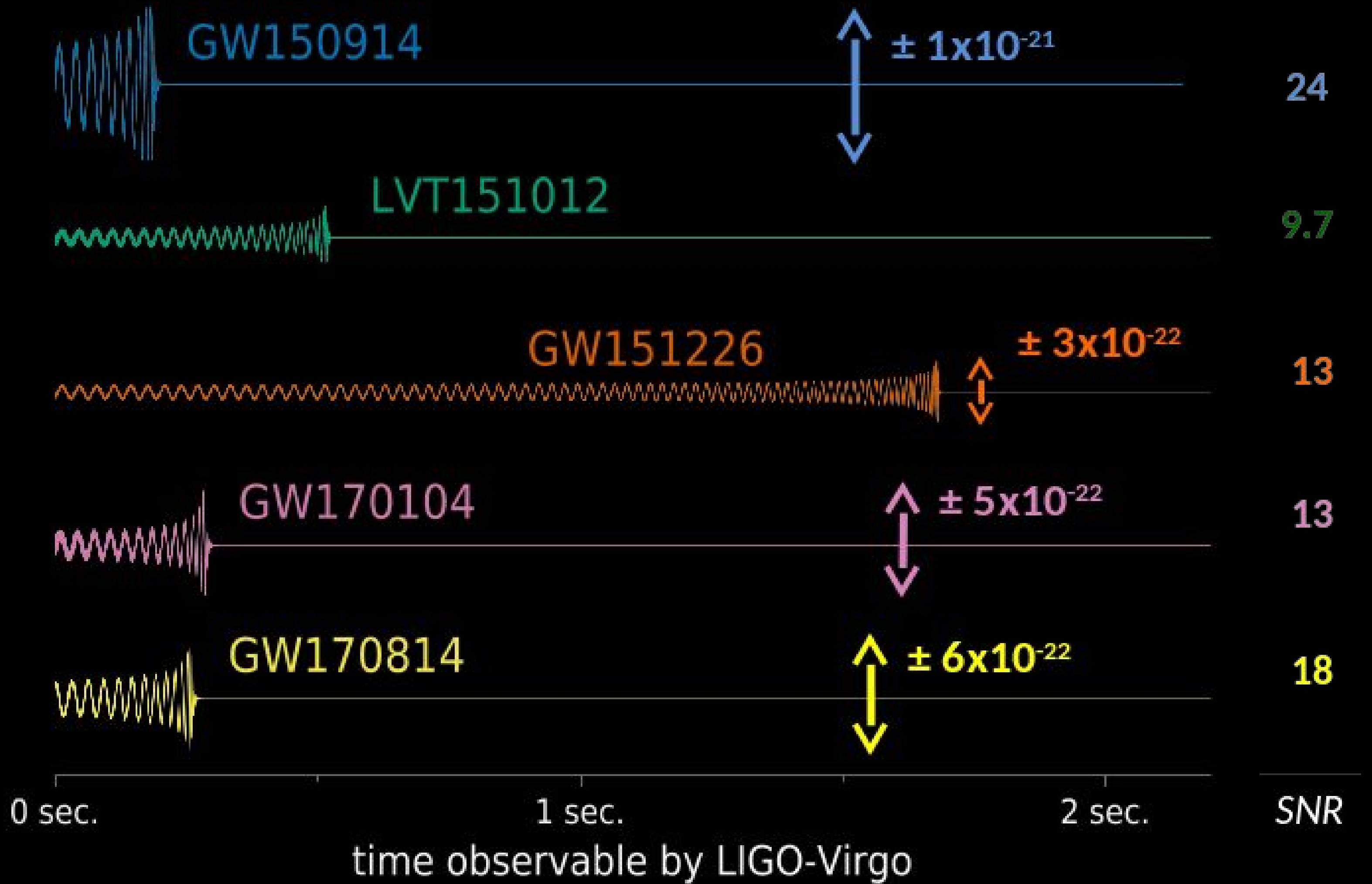
$$H_0 = 70.0^{+12.0}_{-8.0} \text{ km s}^{-1} \text{ Mpc}^{-1}$$

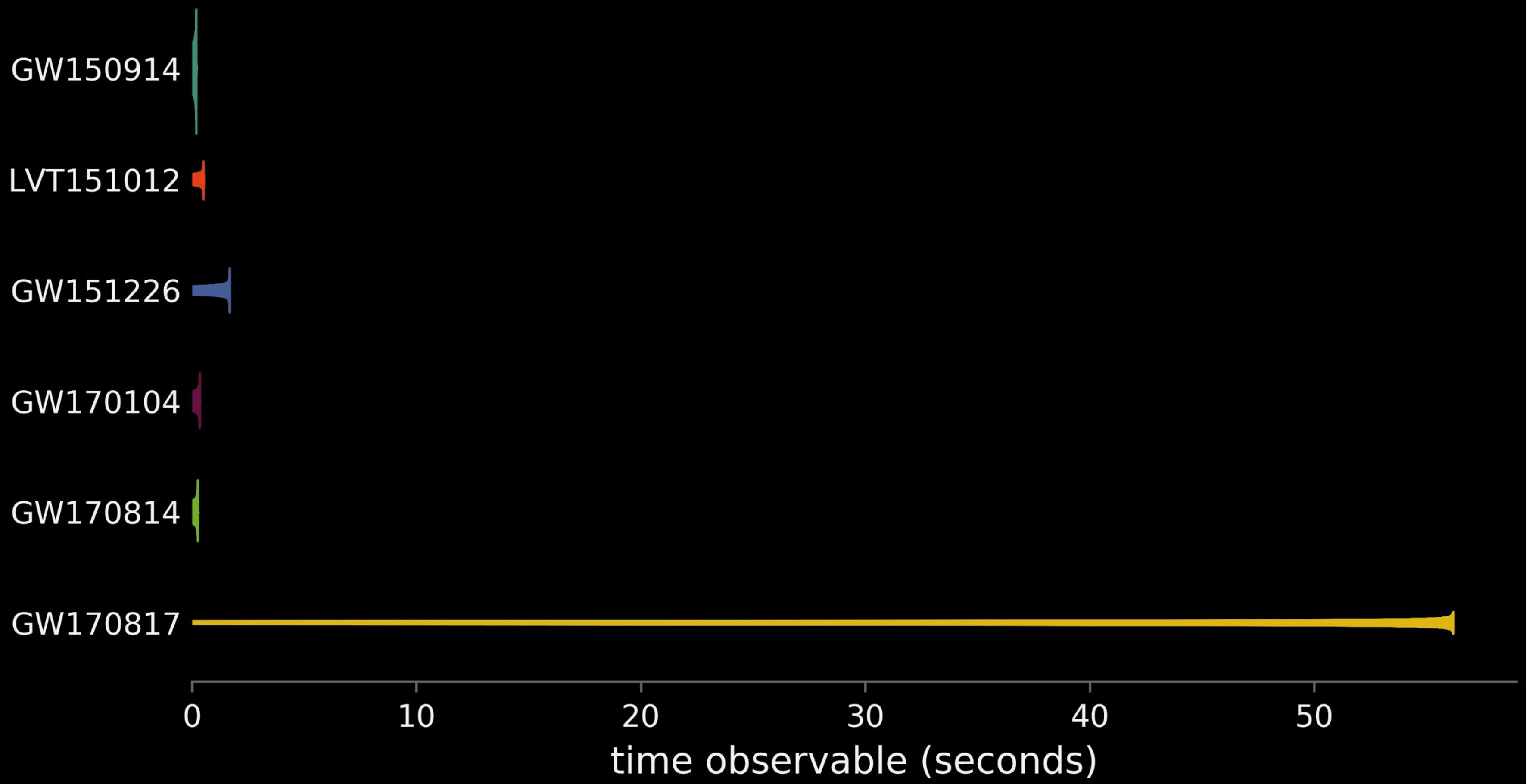
68.3% credible interval

B. P. Abbott et al., *A Gravitational-Wave Standard Siren Measurement of the Hubble Constant*, Nature XX, XX (2017)

Papers from LIGO-Virgo and partners

- B. P. Abbott et al., *GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral*, Phys. Rev. Lett., 119, 161101 (2017)
- B. P. Abbott et al., *Gravitational Waves and Gamma Rays from a Binary Neutron Star Merger: GW170817 and GRB170817A*, ApJL, XX LXX (2017)
- B. P. Abbott et al., *Multi-messenger Observations of a Binary Neutron Star Merger*, ApJL, XX, LXX (2017)
- B. P. Abbott et al., *A gravitational-wave standard siren measurement of the Hubble constant*, Nature, XX, XX (2017)
- B. P. Abbott et al., *Gravitational-wave Search for a Post-Merger Remnant of the Binary Neutron Star Merger GW170817*, available on papers.ligo.org
- B. P. Abbott et al., *Estimating the Contribution of Dynamical Ejecta in the Kilonova Associated with GW170817*, available on papers.ligo.org
- B. P. Abbott et al., *On the progenitor of binary neutron star merger GW170817*, available on papers.ligo.org
- B. P. Abbott et al., *GW170817: Implications for the Stochastic Gravitational-Wave Background from Compact Binary Mergers*, available on papers.ligo.org

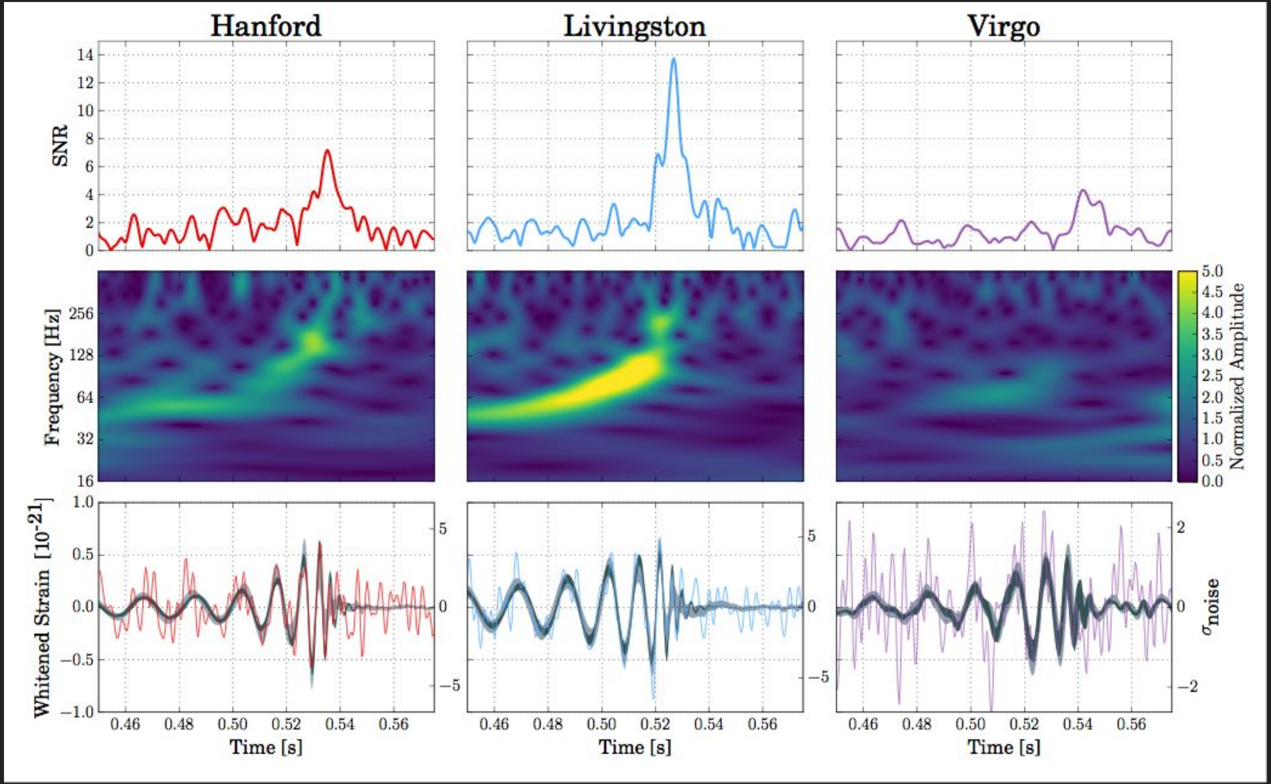

GW150914
± 1x10-21
24
LVT151012
9.7
GW151226
± 3x10-22
13
GW170104
± 5x10-22
13
GW170814
± 6x10-22
18
0 sec.
1 sec.
2 sec.
SNR
time observable by LIGO-Virgo



LIGO/Virgo/University of Oregon/Ben Farr

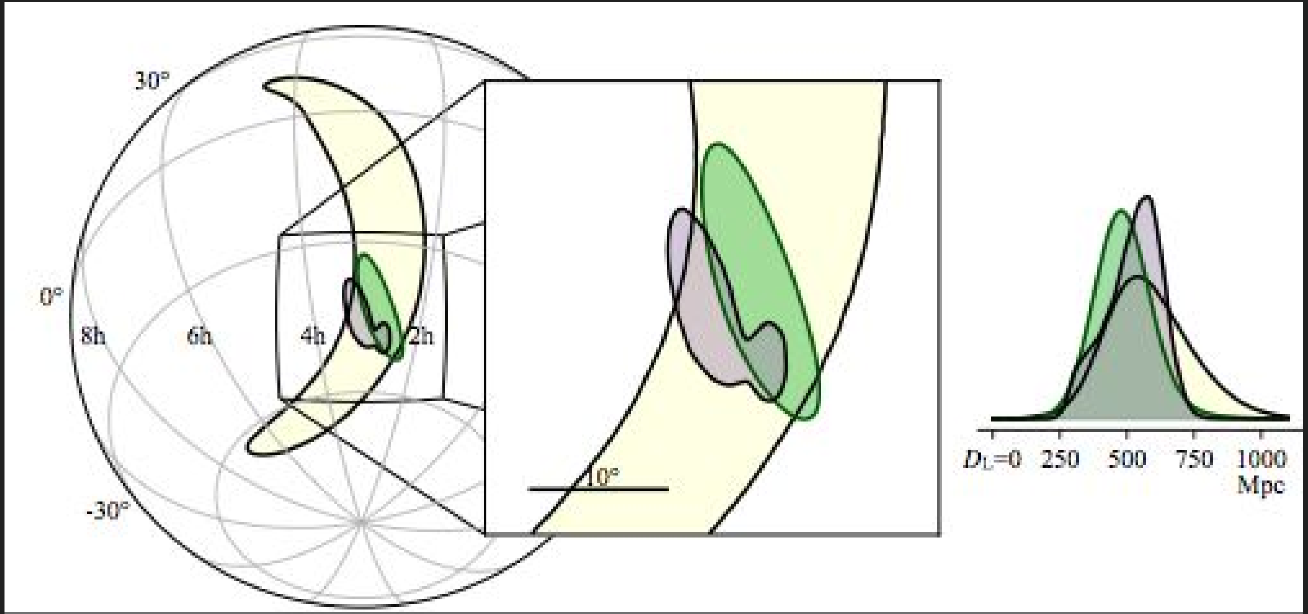
GW170814

The first GW signal observed by LIGO-Hanford, LIGO-Livingston and Virgo



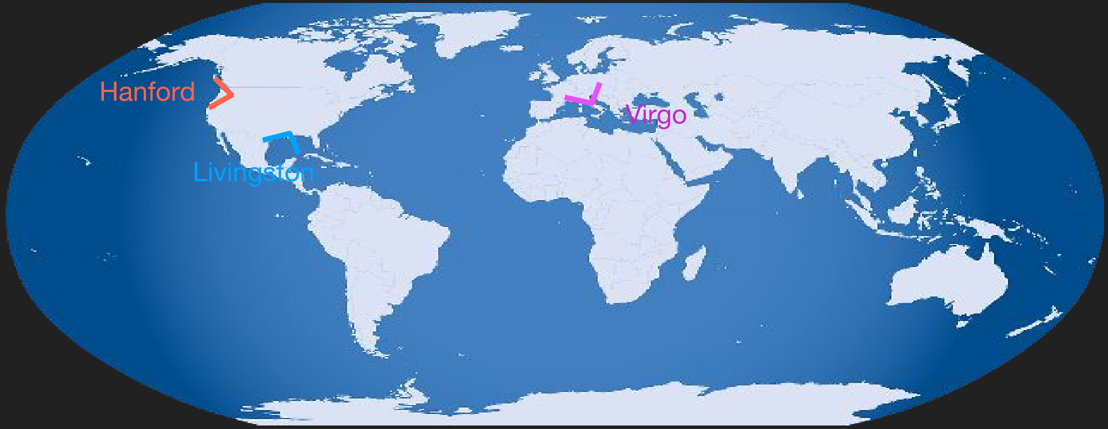
B. P. Abbott et al., *A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence*, Phys. Rev. Lett., 119, 141101 (2017)

GW170814



The inclusion of Virgo means the sky localisation improves from 1160 deg^2 to 60 deg^2

GW170814



LIGO-Hanford and Livingston have similar orientations -> little information about GW polarizations

With Virgo in the network we can project the GW amplitude onto the 3 detectors -> learn about the nature of GW polarizations

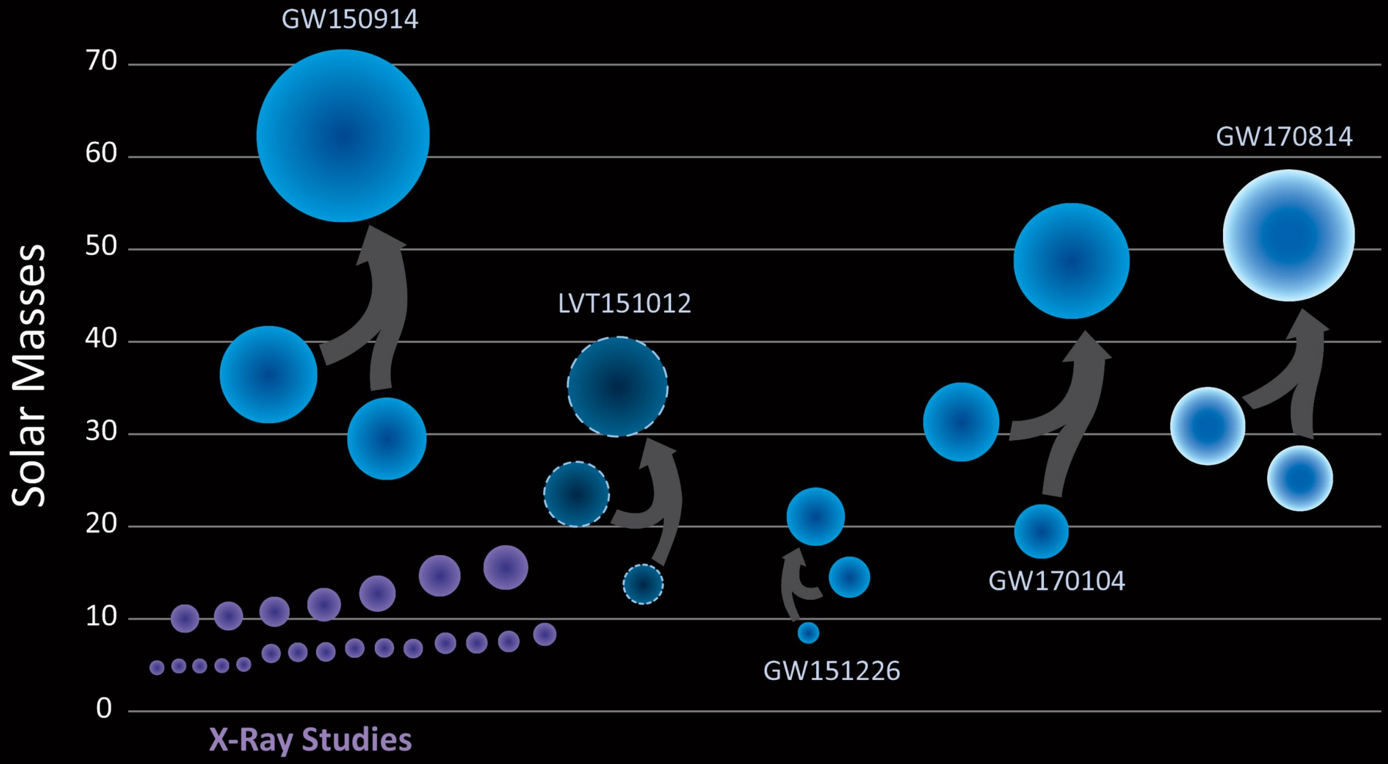
General Relativity predicts metric perturbations possess 2 tensor degrees of freedom

Generic metric theories of gravity allow 6 independent modes - any combination of tensor (2-spin), vector (spin-1), scalar (spin-0) polarizations

Simple test of gravity - consider models where polarisation states are pure tensor, pure vector or pure scalar only

Purely tensor polarization is strongly favored over purely scalar or vector polarizations

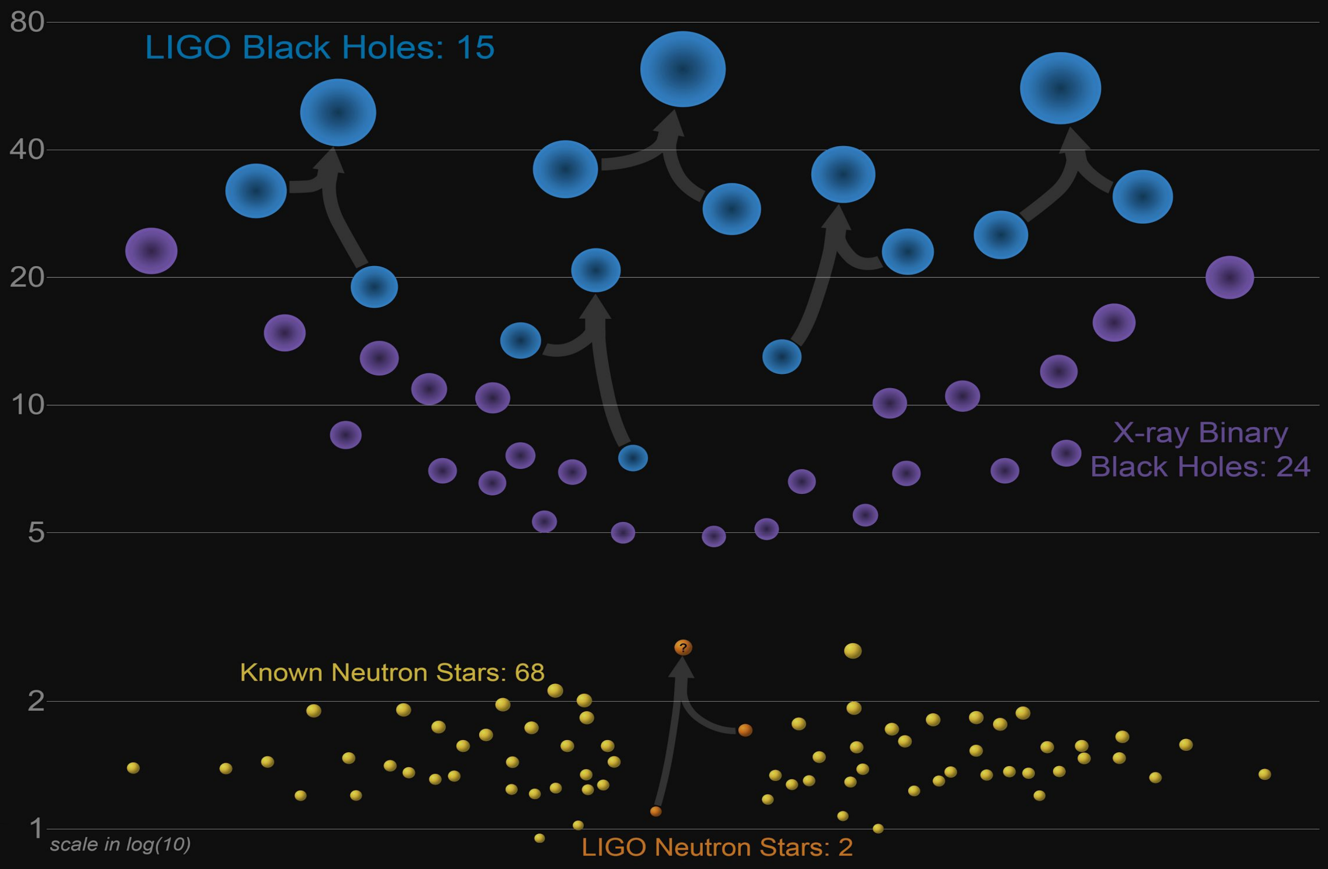
Black Holes of Known Mass



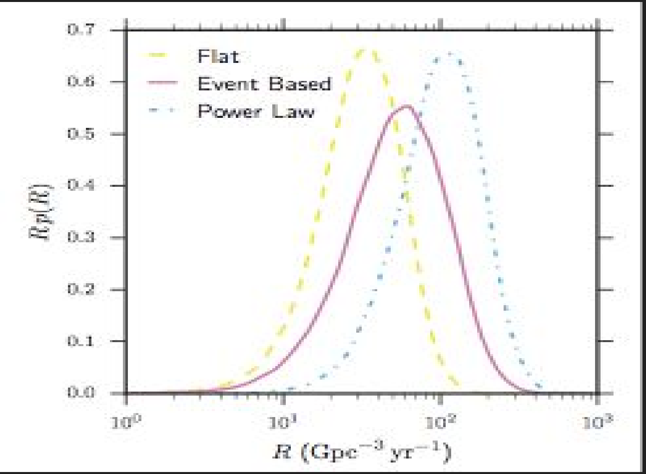
LIGO/VIRGO

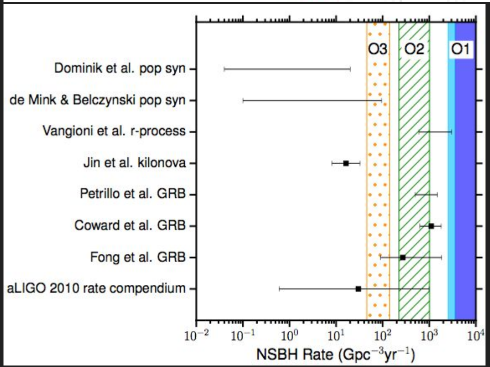
Masses in the Stellar Graveyard

in Solar Masses



Rates of compact object mergers





Binary Black Hole Merger Rate

- Based on O1 BBH mergers: 9-240 Gpc^{-3} yr^{-1}
- Addition of GW170104, BBH merger rate: 12-213 Gpc^{-3} yr^{-1}
- Observation of GW170814 consistent with existing population

Binary Neutron Star Merger Rate

- Based on O1 non-detections: $<$ 12,600 Gpc^{-3} yr^{-1}
- Based on GW170817: 320-4740 Gpc^{-3} yr^{-1}

Neutron Star - Black Hole Merger Rate

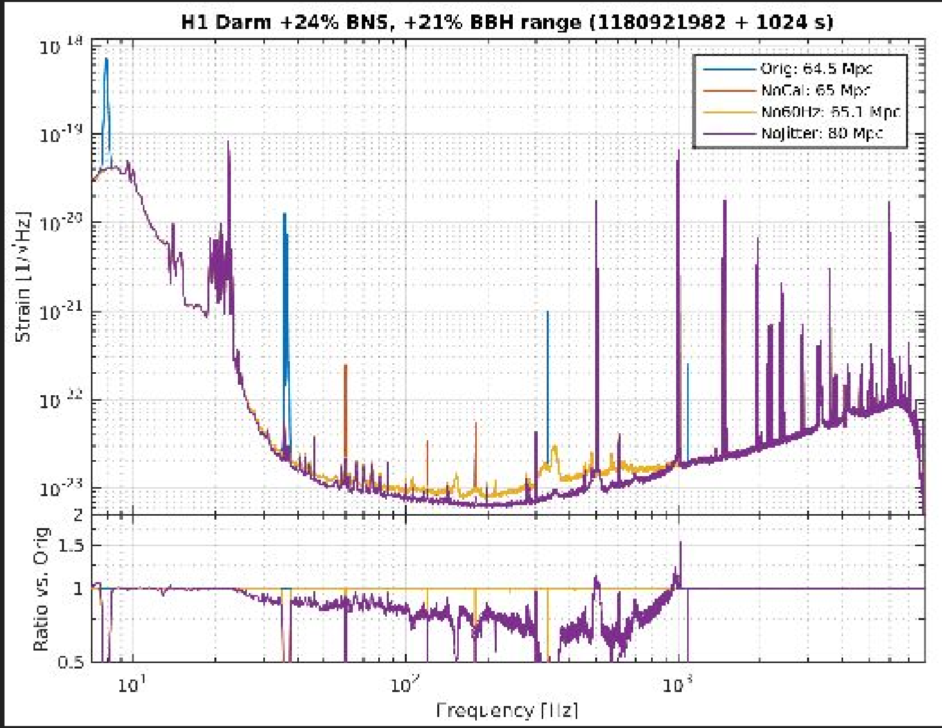
- Based on O1 non-detections (black hole mass $> 5\ M_{\odot}$)
- $<$ 3,600 Gpc^{-3} yr^{-1}

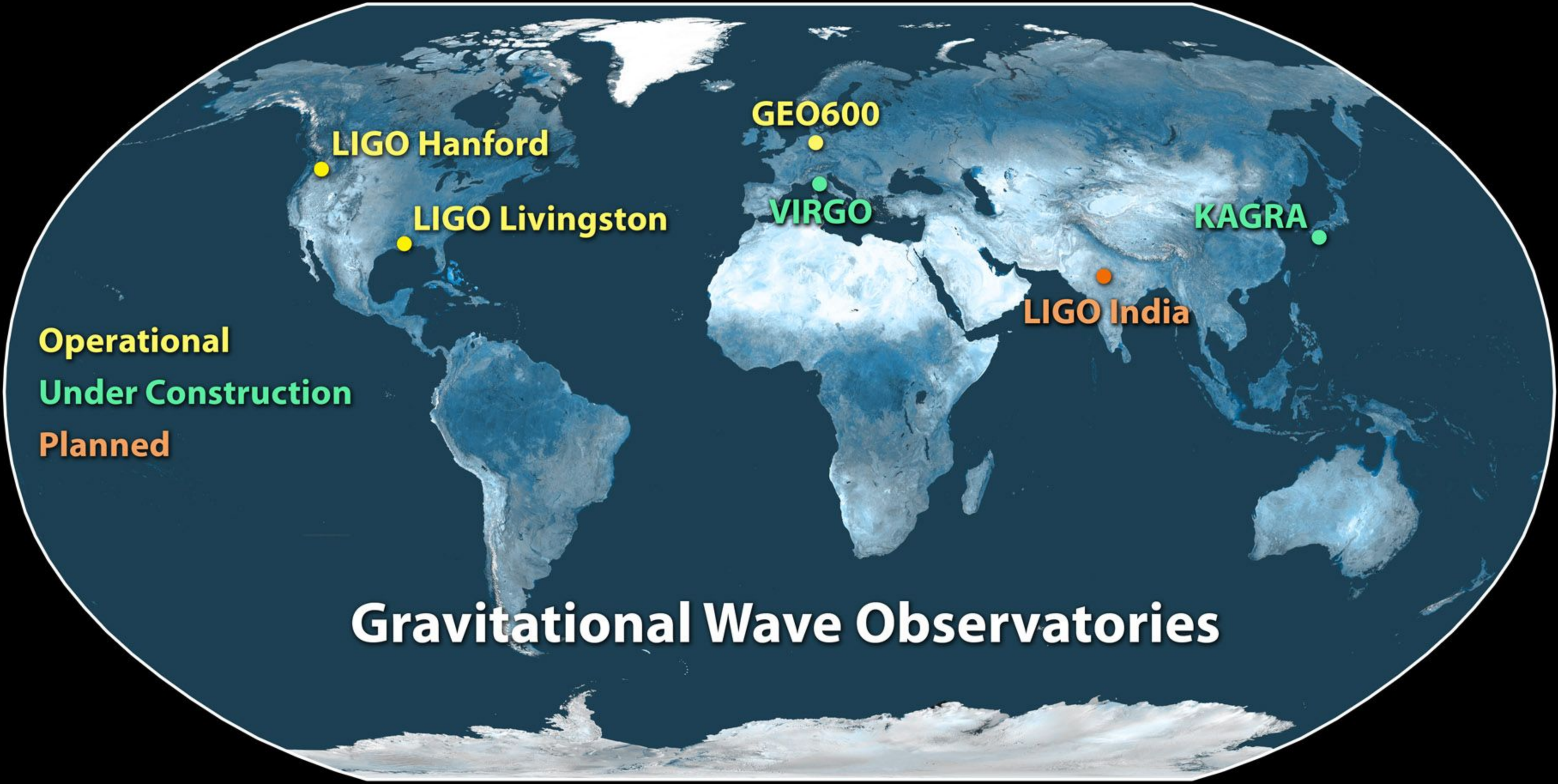
B. P. Abbott et al., *Binary Black Hole Mergers in the First Advanced LIGO Observing Run*, Phys. Rev. X 6, 041015 (2016)
B. P. Abbott et al., *GW170401: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2*, Phys. Rev. Lett., 118, 221101 (2017)
B. P. Abbott et al., *Upper limits on the rates of binary neutron star and neutron-star--black-hole mergers from Advanced LIGO's first observing run*, ApJL, L21 (2016)

So far we’ve only released some of our O2 results - so stay tuned!

More to come from O2

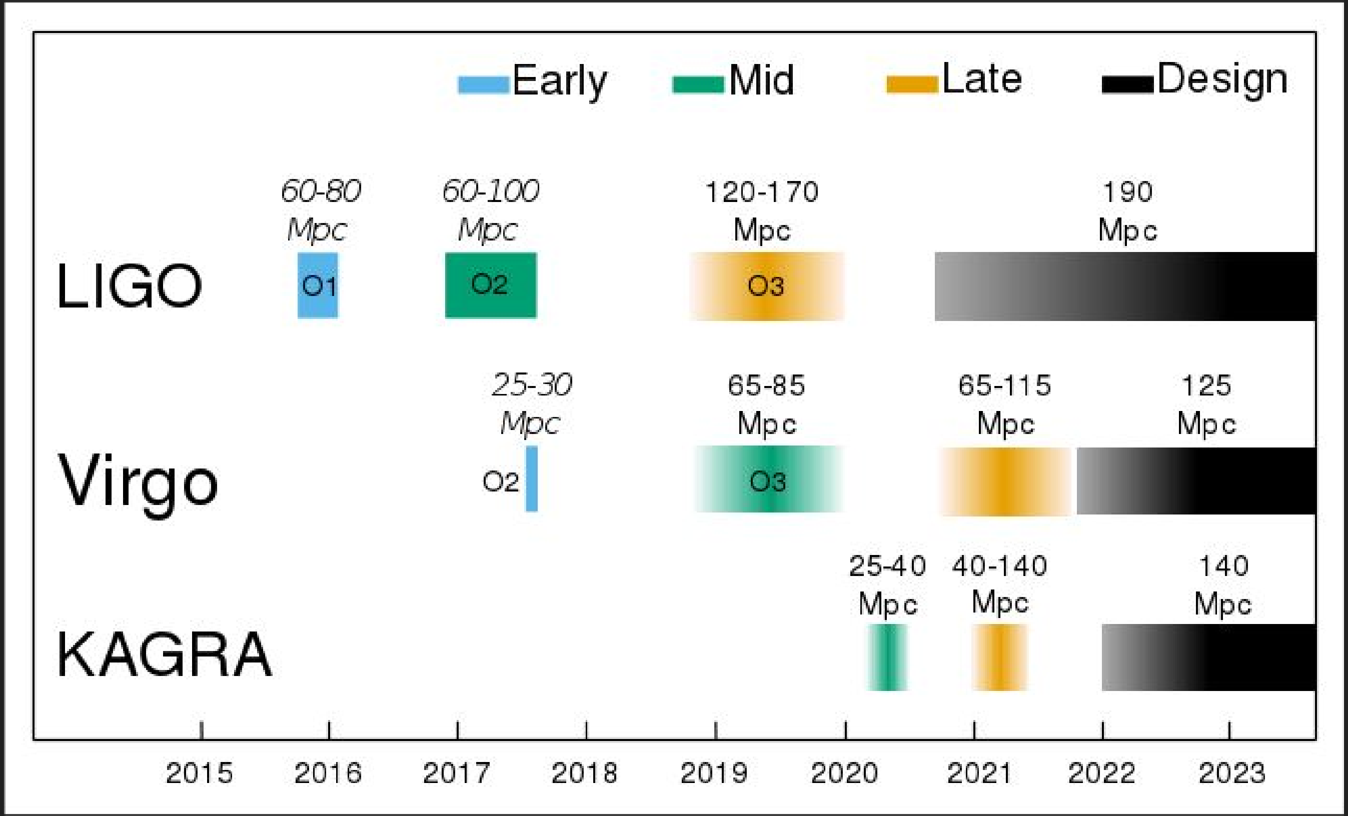
- Not all O2 results reported on.
- The Hanford-LIGO instrument can do significantly better
  - Laser beam motion caused excess noise
  - Currently this noise has been subtracted around the time of detections.
  - Work is underway to do so for the entirety of O2





GEO600
LIGO Hanford
LIGO Livingston
VIRGO
KAGRA
LIGO India
Operational
Under Construction
Planned
Gravitational Wave Observatories

Future Observing



From LIGO-P1200087-v42


Greenland
Iceland
Finland
Sweden
Norway
Russia
Canada
Germany
Ukraine
Kazakhstan
Mongolia
Spain
Turkey
China
South Korea
Japan
North Atlantic Ocean
Iraq
Iran
Afghanistan
Pakistan
Algeria
Libya
Egypt
Saudi Arabia
Mexico
Thailand
Mali
Niger
Sudan
Chad
Nigeria
Ethiopia
Venezuela
Colombia
Kenya
DR Congo
Tanzania
Indonesia
Papua New Guinea
Brazil
Peru
Angola
Bolivia
Namibia
Madagascar
Indian Ocean
Botswana
South Pacific Ocean
Chile
South Atlantic Ocean
Australia
South Africa
Argentina
New Zealand
Southern

Questions?